Assessment of a Point-of-Use Ultrafiltration System for Turbidity and Microbial Pathogen Removal

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U.S. EPA's Office of Research and Development has been evaluating the performance of point-of-use (POU) devices designed for use in homes and small businesses for many years. In collaboration with the University of Cincinnati, a series of pilot-scale tests were conducted on a Matrix Membranes ultrafiltration (MMUF) system at the U.S. EPA Test and Evaluation Facility in Cincinnati, Ohio. The MMUF system operates at a low flow rate (< 2 gpm) and feed pressure (< 30 psi). The polyethersulfone (PES) membrane (2" x 21") is designed for high flux rates with inside-out operation. Membrane integrity tests require the injection of compressed air (10 psi) into the closed system to check for breakthrough or air bubbles in the membrane. The MMUF system requires back-flushing when the filtrate flow drops 25%. The chlorine resistant membrane consists of 500 hollow fibers with 0.8 mm inner diameter and 1.50 mm outer diameter and contains 5.67 square feet of filter surface area. The membrane is cleaned with chlorine (2-200 mg/L) at pH 11 using sodium hydroxide. The membrane has an average pore size of 0.2 µm and a Molecular Weight Cut-off of 100,000. The research study evaluated removal of turbidity (2, 5, and 10 ntu) and microbial surrogates (3 micron polystyrene latex (PSL) beads, MS-2 bacteriophage, and *E. coli*). Other parameters of interest included system flux, runtime, raw water characteristics, and operating cost. Results are summarized and presented on turbidity and microbial removal efficiency.

Introduction

U.S. EPA's Office of Research and Development has been evaluating the performance of point-of-use (POU) devices designed for use in homes and small businesses for many years. The Surface Water Treatment Rules (SWTR) strengthen filtration requirements and provide protection against disinfection-resistant microbial pathogens such as *Cryptosporidium* in drinking water. The SWTR does not require source water monitoring for filtered small systems providing a minimum 5.5 log removal of *Cryptosporidium*, The SWTR sets the turbidity performance standard at less than or equal to 0.15 nephelometric turbidity units (NTU) in at least 95 percent of measurements taken each month with a maximum level of 1 NTU. The objective of the Matrix Membranes Ultrafiltration (MMUF) evaluation study was to determine the capabilities of the MMUF system for producing clean and safe drinking water in compliance with the SWTR.

Background

The MMUF was tested in a small scale system set up to assess one membrane. Figure 1 shows a picture of the bench-scale Matrix Membrane test unit. The system operates at a flow rate of 0.2 to 2 gallons per minute (gpm) of feed water. The water from the 2 liter feed tank is pumped to the membrane with a 115 Volt diaphragm pump and exits in two streams; the filtrate stream and the reject stream. The filtrate stream or finished water is sent to the 1.5 liter filtrate tank. The system in process mode, as shown in Figure 2, can be operated in two different modes; a single pass mode and a recycle mode.

Mode 1 – Single pass mode. Source water (raw water to be treated) is collected in the feed tank of the MMUF system. From the feed tank, the water is pumped through the MMUF system and exits in two streams; a filtrate stream and a reject stream. The filtrate stream can be collected in the system filtrate tank for analysis or discharged to drain. The reject water is discharged to drain in this mode of operation.

Mode 2 – Recycle mode. Source water is collected in the feed tank and is pumped through the MMUF system. The filtrate stream or finished water can be collected in the system filtrate tank for analysis or discharged to drain. The reject water in this mode of operation is fed back into the feed tank and is reprocessed through the MMUF system.

The membrane assessed in this lab-scale study is 2" x 21" (inside-out operation) made from polyethersulfone (PES), manufactured by Matrix Membranes (serial number PES01-010107F). The membrane module is comprised of 500 hollow fibers and element square footage of 5.67 and average pore size of 0.2 µm. Each hollow fiber has a 0.8 mm inner diameter and a 1.50 mm outer diameter. Feed pressure is not to exceed 30 pounds per square inch (psi) and backpressure is not to exceed 20 psi with a maximum transmembrane pressure (TMP) of 30 psi. The maximum operating temperature is 120ºF with a pH range of 2 to 12. The preservative recommended for storing the membrane is 0.5% m-bisulfite and 25% glycerin. The membrane is equipped with a removable cap for fiber repair.

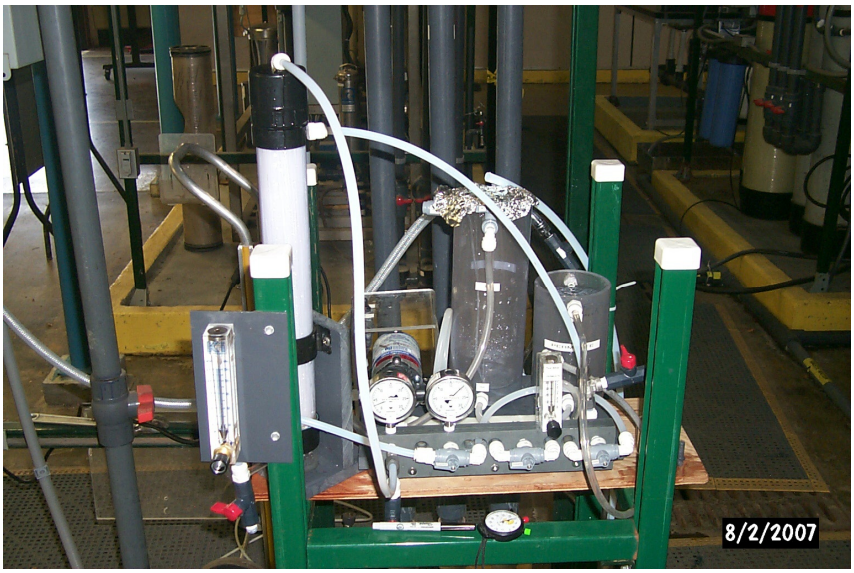

Figure 1. Bench-Scale Matrix Membrane Unit

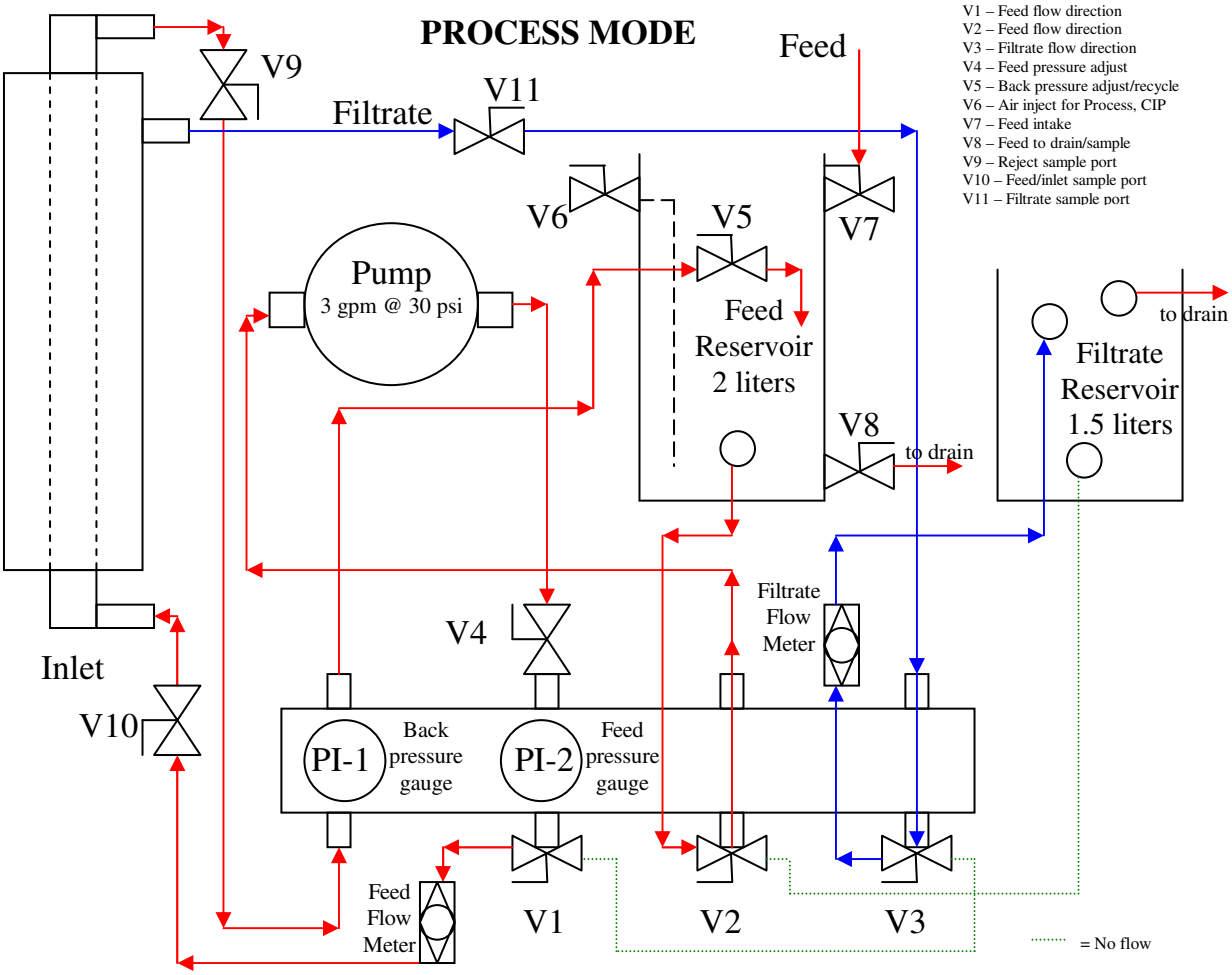

Figure 2. Schematic Diagram of Pilot-Scale MMUF System in Process Mode

While in operation, the backpressure valve (V5) and feed flow meter are adjusted in order to maintain steady state conditions and control the pressure in the system.

The bench scale system also operates in back-flush mode and CIP (clean-in-place) mode. Figure 3 illustrates the system in back-flush mode, which is an inside-out operation, and Figure 4 illustrates the system in CIP mode. Back-flush mode is utilized when the flux drops 25%, which is indicated by a drop in the filtrate flow rate. When the back-flush mode is no longer effective for cleaning the membrane, CIP mode is employed. CIP uses a solution of sodium hydroxide at a pH of 11 and chlorine ranging from 2 to 200 ppm(v). The system is recycled at 5 to 10 psi with no back pressure for 30 minutes. The system is then flushed until the pH is neutral and back-flush mode is utilized with approximately one liter of filtrate.

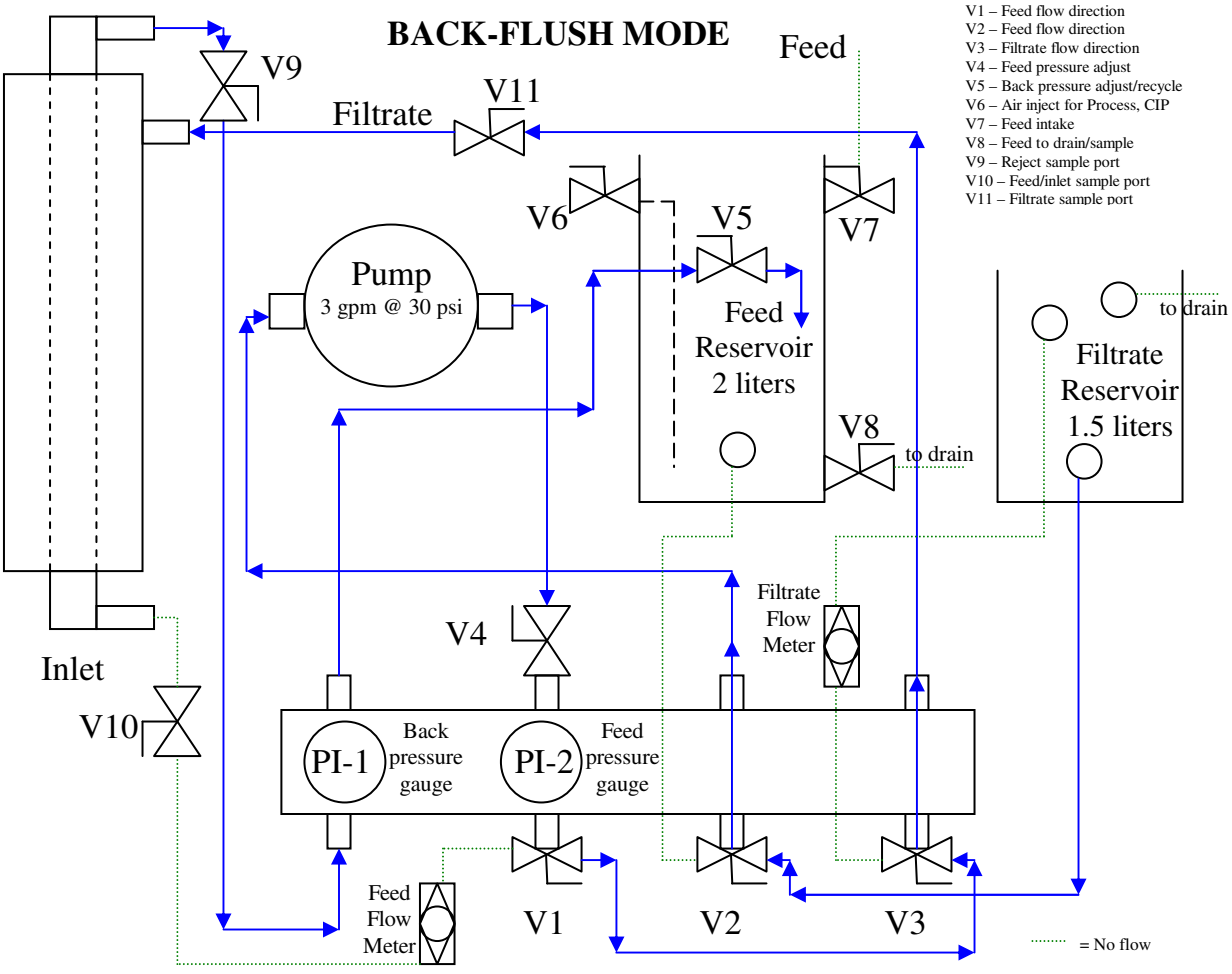

Figure 3. Schematic Diagram of Pilot-Scale MMUF System in Back-Flush Mode

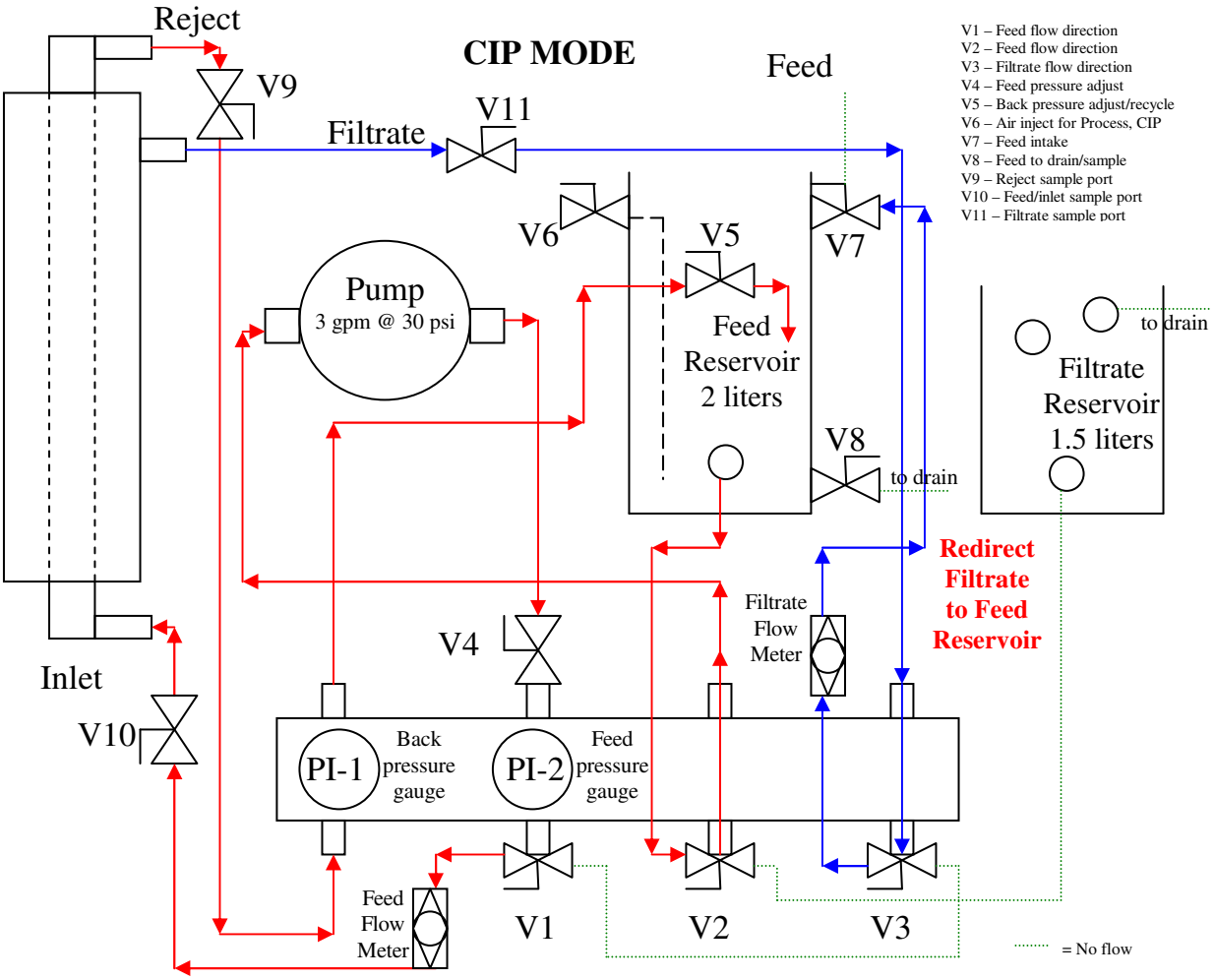

Figure 4. Schematic Diagram of Pilot-Scale MMUF System in CIP Mode

The air inject (V6) can be utilized for cleaning the tubing at low pressure with high velocity and it may also be employed for integrity testing. The integrity test involves switching the intake valve from water to air inlet, closing all valves for a few minutes, and pressurizing the system to 10 psi while observing any break-through air bubbles in the membrane.

Experimental Results

The objective of the MMUF study was to determine the capabilities of the MMUF system for producing clean and safe drinking water focusing on the removal of turbidity and microorganisms, such as protozoa, bacteria, and viruses. The following outlines the various microbes and surrogates that were used to challenge the MMUF system.

- Turbidity tests with feed water turbidities of 2 NTU, 5 NTU, and 10 NTU, with two repeat tests conducted at these conditions
- Three protozoa tests with dechlorinated tap water and Polystyrene Latex (PSL) beads
- Three virus tests with dechlorinated tap water and MS2 bacteriophage
- Three bacteria tests with dechlorinated tap water and *Escherichia coli* (*E. coli*)

The MMUF system was operated in recycle mode during the experiments. The reject water in this mode of operation is fed back into the feed tank and is reprocessed through the MMUF system.

Table 1 outlines the experimental design parameters for the MMUF Study. Table 2 lists the test conditions that were employed to challenge the MMUF system. Conditions 1 through 3 were conducted with a mixture of Cincinnati tap water and Mill Creek water (an industrial tributary of the Ohio River) to achieve the desired turbidity. Duplicate runs were conducted for each turbidity level for these conditions. Conditions 4 through 6 were conducted with dechlorinated Cincinnati tap water. During the test runs employing dechlorinated tap water, free and total chlorine samples were taken to document the extent of dechlorination. Table 3 provides experimental measurements for comparison with Tables 1 and 2.

Table 1. Experimental Design Parameters

Parameters	Selected Values
Source water	Dechlorinated tap water
Target contaminant	Microbial surrogates
Concentration of contaminant	4 levels to be determined
Temperature	Ambient temperature, maximum 120ºF, also feed and filtrate temperature
Feed Flow rate	0 to 40 gph
Filtrate Flow rate	0 to 40 gph
Feed pressure	0 to 20 psi
Back pressure	0 to 20 psi
pH	2 to 12, feed and filtrate pH
Test Duration	4 hours

Table 2. Test Conditions

Test Run	Evaluation Parameter	Turbidity (NTU)	Microbe/ Surrogate	Water Matrix
Condition 1	Turbidity	~2	None	Tap water + Mill Creek Water
Condition 2	Turbidity	~5	None	Tap water + Mill Creek Water
Condition 3	Turbidity	~10	None	Tap water + Mill Creek Water
Condition 4	Protozoa	As received	PSL beads	Dechlorinated tap water
Condition 5	Virus	As received	MS2 bacteriophage	Dechlorinated tap water
Condition 6	Bacteria	As received	*E. coli*	Dechlorinated tap water

Table 3. Experimental Measurements

Condition and Run Number	Parameter	Total Sampling Time (min)	Ave. Feed Flow Rate (gph)	Ave. Filtrate Flow Rate (gph)	Ave. Feed Pressure (psi)	Ave. Back Pressure (psi)	Average Water Temp (ºC)
1-1	Turbidity	180	79.8	16.1	23.3	17.7	30.1
1-2	Turbidity	120	79.4	15.6	23.7	18.3	30.3
2-1	Turbidity	120	70.8	11.2	27.9	17.8	28.7
2-2	Turbidity	120	70.0	11.0	28.3	18.3	30.5
3-1	Turbidity	120	69.9	10.5	28.2	17.8	28.3
3-2	Turbidity	120	69.0	9.9	28.1	18.2	29.1
4-1	PSL Beads	130	60	4	19.5	4	27
4-2	PSL Beads	120	87	4	19	4	30
4-3	PSL Beads	130	87	4	19	3.5	32
5-1	MS2	7	72	4	26.5	1.5	28.5
5-2	MS2	6.5	64.5	4	29.5	5.3	27
5-3	MS2	7	93	3	16.3	2.8	26.5
6-1	*E. coli*	7	15	2	18	2	28
6-2	*E. coli*	6	15	2	17.5	2	30
6-3	*E. coli*	7	54	2	20	1	31

Evaluation Objectives

To determine removal efficiency, samples were collected from the feed, filtrate, and reject water streams. These samples were analyzed for microbes/surrogates as appropriate. The log removal efficiency was calculated as follows:

$$\text{Log Removal Value} = \text{Log}\left[\frac{\text{count of microbes or surrogates in feed water}}{\text{count of microbes or surrogates in permeate water}}\right]$$

$$LRV = \log(C_f) - \log(C_p)$$

Where, LRV = Log Removal Value demonstrated during a challenge test

Co = feed concentration of the challenge particulate (number or mass/volume)

Ce = filtrate concentration of the challenge particulate (number or mass/volume)

Filtrate flux values were reported in terms of temperature-corrected flux values, as gallons per square foot per day (gfd) at 68ºF. The average filtrate flux is the flow of product water divided by the surface area of the membrane. Filtrate flux is calculated according to the following formula:

$$J_t = \frac{Q_p}{S}$$

Where, J_t = filtrate flux at time t (gfd)

Q_p = filtrate flow (gpd)

S = membrane surface area (ft^2)

The average transmembrane pressure is calculated by the following relation:

$$P_{tm} = P_f - P_p$$

Where, P_{tm} = transmembrane pressure (psi)

P_f = feed pressure (psi)

P_p = filtrate pressure, or back pressure (psi)

For a UF process, the temperature correction factor (TCF) is defined as the ratio of the viscosity at temperature T to the viscosity at 20ºC (68ºF), as shown in the following:

$$TCF = \frac{\mu_T}{\mu_{20}}$$

Where, TCF = temperature correction factor (dimensionless)

$\mu_T = 1.784 - (0.0575 \times T) + (0.0011 \times T^2) - (10^{-5} \times T^3)$ (cp), the viscosity of water at temperature T,ºC

μ_{20} = viscosity of water at temperature 20ºC (cp)

The temperature-normalized flux can be expressed in simplified terms in the equation:

$$J_{20} = J_t \times TCF$$

Where, J_{20} = normalized flux at 20ºC (gfd)

J_t = actual flux at temperature T,ºC (gfd)

TCF = temperature correction factor (dimensionless)

In order to identify changes in productivity (as measured by flux) that are specifically attributable to membrane fouling, it is desirable to normalize the flux for pressure as well as temperature, as shown in the following relationship. Specific flux, or permeability, refers to the filtrate flux that has been normalized for the transmembrane pressure and temperature. Specific flux results are reported with indication of the time interval after initiation of the experimental test run. The equation used for calculation of specific flux is given as follows:

$$J_{tm} = \frac{J_{20}}{P_{tm}}$$

Where, J_{tm} = temperature and pressure normalized flux (specific flux) at time t (gfd/psi)

J_{20} = normalized flux at 20ºC (gfd)

P_{tm} = transmembrane pressure (psi)

The recovery of filtrate from the feed water is given as the ratio of filtrate flow to feed water flow:

$$\%\ \text{System Recovery} = 100 \times \left[\frac{Q_p}{Q_f} \right]$$

Where, Q_p = filtrate flow (gpd)

Q_f = feed flow to the membrane (gpd)

The recovery of filtrate from total recirculation influent water is given as the ratio of filtrate flow to the sum of feed water flow and recycle flow, as described by the following equation:

$$\% \text{ Element Recovery} = 100 \times \left[\frac{Q_p}{Q_f + Q_r} \right]$$

Where, Q_p = filtrate flow (gpd)
Q_f = feed flow to the membrane (gpd)
Q_r = recycle flow (gpd), assume $Q_r = Q_f - Q_p$

Table 4 provides measured evaluation parameters for all conditions and experimental runs.

Table 4. Evaluation Parameters

Condition and Run Number	Parameter	Average Filtrate Flux, J_t (gfd)	Average Transmembrane Pressure, P_{tm} (psi)	Temp. Correction Factor, TCF	Temp-normalized Flux, J_{20} (gfd)	Specific Flux, J_{tm} (gfd/psi)	% System Recovery	% Element Recovery
1-1	Turbidity	68.3	5.6	0.78	53.4	9.6	20.2	11.3
1-2	Turbidity	65.9	5.4	0.78	51.4	9.6	19.6	10.9
2-1	Turbidity	47.3	10.1	0.81	38.3	3.8	15.8	8.6
2-2	Turbidity	46.6	10.1	0.77	36.1	3.6	15.7	8.5
3-1	Turbidity	44.5	10.4	0.82	36.4	3.5	15.1	8.1
3-2	Turbidity	41.8	9.9	0.80	33.5	3.6	14.3	7.7
4-1	PSL Beads	16.9	15.5	0.84	14.3	0.92	6.7	3.4
4-2	PSL Beads	16.9	15	0.78	13.3	0.88	4.6	2.4
4-3	PSL Beads	16.9	15.5	0.75	12.7	0.82	4.6	2.4
5-1	MS2	16.9	25	0.81	13.8	0.55	5.6	2.9
5-2	MS2	16.9	24.3	0.84	14.3	0.59	6.2	3.2
5-3	MS2	12.7	13.5	0.85	10.8	0.80	3.2	1.6
6-1	*E. coli*	8.5	16	0.82	7.0	0.43	13.3	7.1
6-2	*E. coli*	8.5	15.5	0.78	6.6	0.43	13.3	7.1
6-3	*E. coli*	8.5	19	0.77	6.5	0.34	3.7	1.9

Turbidity Studies (Conditions 1, 2, and 3)

The MMUF system was operated in continuous mode with recycle for 2 hours of sampling and constant feed of turbid water. Steady-state conditions were maintained over the course of the experiments and the averages flow rates were used in calculations and reporting. Two experiments were performed at each turbidity level. Turbidity grab samples were taken every 30 minutes at each Condition. Table 5 summarizes turbidity removal results for Conditions 1, 2, and 3.

Table 5. Critical Parameter Measurement

	Feed Stream		Filtrate Stream		
Condition and Run Number	***Turbidity (NTU)***	**Particle Counts/mL**	***Turbidity (NTU)***	**Particle Counts/mL**	**% Removal**
1-1	1.8	8,300	0.18	125	89.9
1-2	1.6	9,000	0.14	165	91.2
2-1	4.7	11,000	0.13	140	97.3
2-2	4.0	10,820	0.14	176	96.0
3-1	9.2	>15,000	0.11	140	98.8
3-2	9.0	>15,000	0.12	150	98.7

For all turbidity tests, an in-line particle counter measured the particle count in the feed and filtrate water every 60 minutes. Only the channel measuring particles in the 2 to 5 µm size range was employed, which is comparable in size to *Cryptosporidium*. Because of the low filtrate flow rate, it was difficult to obtain a particle count. The flow dropped considerably while taking particle count and this drop was not accounted for in the overall averages. After each turbidity experiment, the system was back-washed with D.I. water followed by flushing with potable tap water.

Polystyrene Latex Beads Study (Condition 4)

Three tests were conducted with 3 µm PSL beads as a surrogate for *Cryptosporidium* oocysts. These tests were conducted in a single batch with recycle with a total sampling time of approximately 7 minutes. The feed solution was prepared by mixing 1 mL of the PSL bead solution with 500 mL of polysorbate surfactant. This mixture was stirred for approximately 5 minutes. This solution was added to dechlorinated tap water for a total feed volume of 2 liters. After the feed solution went through the system, the membrane was flushed with dechlorinated tap water in continuous mode with recycle for another 2 hours.

All filtrate for this entire time was collected on a 293 mm 1.0 µm PCTE (Polycarbonate Track Etch) membrane filter situated on a manifold membrane unit. The membrane filter was subsequently rinsed using a dilute polysorbate surfactant solution and the rinseate was collected in a sample bottle. A sample aliquot of the initial concentration was taken prior to performing the study. A flow totalizer was used but the flow was too low to get accurate readings.

After the beads were collected with 0.01% Tween®-20 solution as a rinseate, the sample was concentrated with use of a rotor bucket centrifuge. The supernatant water was removed from the top of the centrifuged sample using a vacuum line, leaving 10 mL of concentrated sample. A hemacytometer was utilized to count the fluorescent beads viewed through a microscope. The blank control yielded zero. Tables 6 and 7 summarize PSL bead test results for Condition 4.

Table 6. MMUF PSL Bead Test Results

Sample time, dilution	Run 1 Counts/100 mL	Run 2 Counts/100 mL	Run 3 Counts/100 mL
Beads Injected 10^{-10}	123, 116, 127	132, 135, 132	132, 140, 126
Filtrate 10^{-0}	0, 0, 0	0, 0, 0	0, 0, 0

Table 7. Critical Parameter Measurements for the PSL Bead Study

Condition and Run Number	Co, Counts/100 mL	Ce, Counts/100 mL	*LRV*
4-1	1.53×10^9	0	9.18
4-2	1.66×10^9	0	9.22
4-3	1.66×10^9	0	9.22

MS2 Bacteriophage Study (Condition 5)

Three tests were conducted with MS2 bacteriophage, approximately 23 to 25 nm in size. These tests were conducted in a single batch with recycle with a total sampling time of approximately 7 minutes. The feed solution was prepared by mixing 100 µL of MS2 with dechlorinated tap water for a total feed volume of 2 liters and a starting concentration of 10^8 counts. After the feed solution went through the system, the membrane was flushed with dechlorinated tap water in continuous mode with recycle for another 2 hours. The blank control yielded zero. Tables 8 and 9 provide a summary of MS2 Bacteriophage study results for Condition 5.

Table 8. MMUF MS2 Bacteriophage Test Results

Sample time, dilution	Run 1 MS2/100 mL	Run 2 MS2/100 mL	Run 3 MS2/100 mL
T2 Filtrate 10^{-0}	0	1, 1, 0, 1, 1, 0, 1, 0, 2, 2	TMTC*
T6 Filtrate 10^{-0}	0	1, 2, 0, 1, 0, 0, 0, 1, 1, 1	TMTC
T2 Feed 10^{-4}	98, 110, 100, 107, 98, 104, 96, 97, 102, 105	28, 14, 28, 32, 26, 32, 28, 20, 22, 20	40, 46, 42, 40, 36, 40, 33, 38, 36, 30
T6 Feed 10^{-4}	102, 106, 98, 92, 88, 105, 97, 82, 110, 107	32, 36, 32, 25, 31, 24, 33, 28, 23, 24	46, 36, 36, 45, 36, 40, 44, 42, 41, 39
T2 Reject 10^{-4}	116, 110, 118, 110, 103, 96, 108, 97, 111, 107	NA**	31, 32, 42, 32, 31, 26, 38, 43, 26, 31
T6 Reject 10^{-4}	86, 100, 105, 118, 83, 92, 96, 96, 99, 103	NA	28, 32, 28, 36, 40, 30, 32, 34, 30, 25

*TMTC = Too Many To Count **NA = Data Not Available

Table 9. Critical Parameter Measurements for the MS2 Bacteriophage Study

Condition and Run Number	Co, MS2/100 mL 2 minutes	Ce, MS2/100 mL 2 minutes	*LRV*	Co, MS2/100 mL 6 minutes	Ce, MS2/100 mL 6 minutes	*LRV*
5-1	1.02×10^7	0	7.01	9.85×10^6	0	6.99
5-2	2.50×10^6	9	5.45	2.88×10^6	7	5.61

Run Number 3 was not included in the critical parameters because of suspected contamination. The filtrate samples yielded TMTC and these results not included.

Escherichia Coli Study (Condition 6)

Three tests were conducted with E. coli. These tests were conducted in a single batch with recycle with a total sampling time of approximately 7 minutes. The feed concentration of 10^8 counts in approximately 2,000 mL equates to about a 10^7 bacteria cells/1,000 mL starting concentration. After the feed solution went through the system, the membrane was flushed with dechlorinated tap water in continuous mode with recycle for another 2 hours. The blank control yielded zero. Tables 10 and 11 summarize *E. coli* study results for Condition 6.

Table 10. MMUF *EscherichiaColi* Test Results

Sample time, dilution	Run 1 *E. coli*/100 mL	Run 2 *E. coli*/100 mL	Run 3 *E. coli*/100 mL
T2 Filtrate 10^{-2}	3, 4	**1**	1, 1
T2 Filtrate 10^{-1}	**29***	1, 0	**6**
T6 Filtrate 10^{-2}	2, 2	**10**	0, 1
T6 Filtrate 10^{-1}	**19**	2, 0	**10**
T2 Feed 10^{-4}	TMTC**	TMTC	**20**
T2 Feed 10^{-5}	**14, 7**	**10, 21**	3, 6
T6 Feed 10^{-4}	TMTC	TMTC	**59**
T6 Feed 10^{-5}	**6, 16**	**34, 24**	6, 10
T2 Reject 10^{-4}	52	TMTC	29
T2 Reject 10^{-5}	6, 4	68, 24	10, 9
T6 Reject 10^{-4}	TMTC	TMTC	TMTC
T6 Reject 10^{-5}	12, 16	62, 50	10, 10

*Bold results utilized in calculations, **TMTC = too many to count

Table 11. Critical Parameter Measurements for the *Escherichia Coli* Study

Condition and Run Number	Co, *E.coli*/100 mL 2 minutes	Ce, *E.coli*/100 mL 2 minutes	*LRV*	Co, *E.coli*/100 mL 6 minutes	Ce, *E.coli*/100 mL 6 minutes	*LRV*
6-1	1.05×10^7	290	4.56	1.1×10^7	190	4.76
6-2	1.55×10^4	10	6.19	2.9×10^7	100	5.46
6-3	2×10^6	60	4.52	5.9×10^6	100	4.77

After each PSL Bead, MS2 Bacteriophage, and *E.coli* experimental run, the feed and filtrate tank were each treated with 2 pellets of NaOH and 50 µL of bleach in D.I. water and then rinsed four times with tap water in continuous mode with recycle. Steady state conditions were maintained throughout each experiment and an average reading over the sampling time was recorded. Total and free chlorine in dechlorinated tap water for all surrogate studies was less than 0.04 mg/L.

CONCLUSIONS

Based on the preliminary experiments conducted to date, the ultrafiltration membrane appears to be a consistent and effective technology for producing drinking water that meets regulatory requirements for turbidity and *Cryptosporidium*. The MMUF system also effectively removed the microorganisms *Escherichia coli* and MS2 bacteriophage.

- MMUF system produced water with a turbidity level of <0.18 NTU
- The removal of particles (2 to 5 µm) was approximately 98%
- The 3 µm PSL bead study illustrated capability of 9-log removal
- The MMUF system was capable of 6-log removal of MS2 bacteriophage
- The MMUF system was capable of 5-log removal of *Escherichia coli*

The Surface Water Treatment Rules do not require source water monitoring for filtered systems with a 5.5-log physical removal of *Cryptosporidium*. The MMUF system analyzed in this study surpassed this requirement by producing water with 9-log removal of PSL beads, a surrogate for *Cryptosporidium.* It also establishes increased turbidity monitoring requirements and sets the turbidity performance standard at ≤0.15 nephelometric turbidity units (NTU) in at least 95 percent of measurements taken each month with a maximum level of 1 NTU. One of the six turbidity test runs exceeded this monitoring requirement with an average effluent turbidity result of 0.18 NTU.

The following conclusions and recommendations can be made from the results of this performance evaluation:

- The results from all experiments were within 15%, indicating repeatable results from the MMUF system.
- Samples were taken in increasing turbidity levels and the performance of the membrane increased with increasing turbidity level
- Overall, there was a decrease in feed and filtrate flow over the course of the experiments. Over a two hour turbidity test, the filtrate flow decreased on average 20% and the feed flow decreased on average 2%.

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